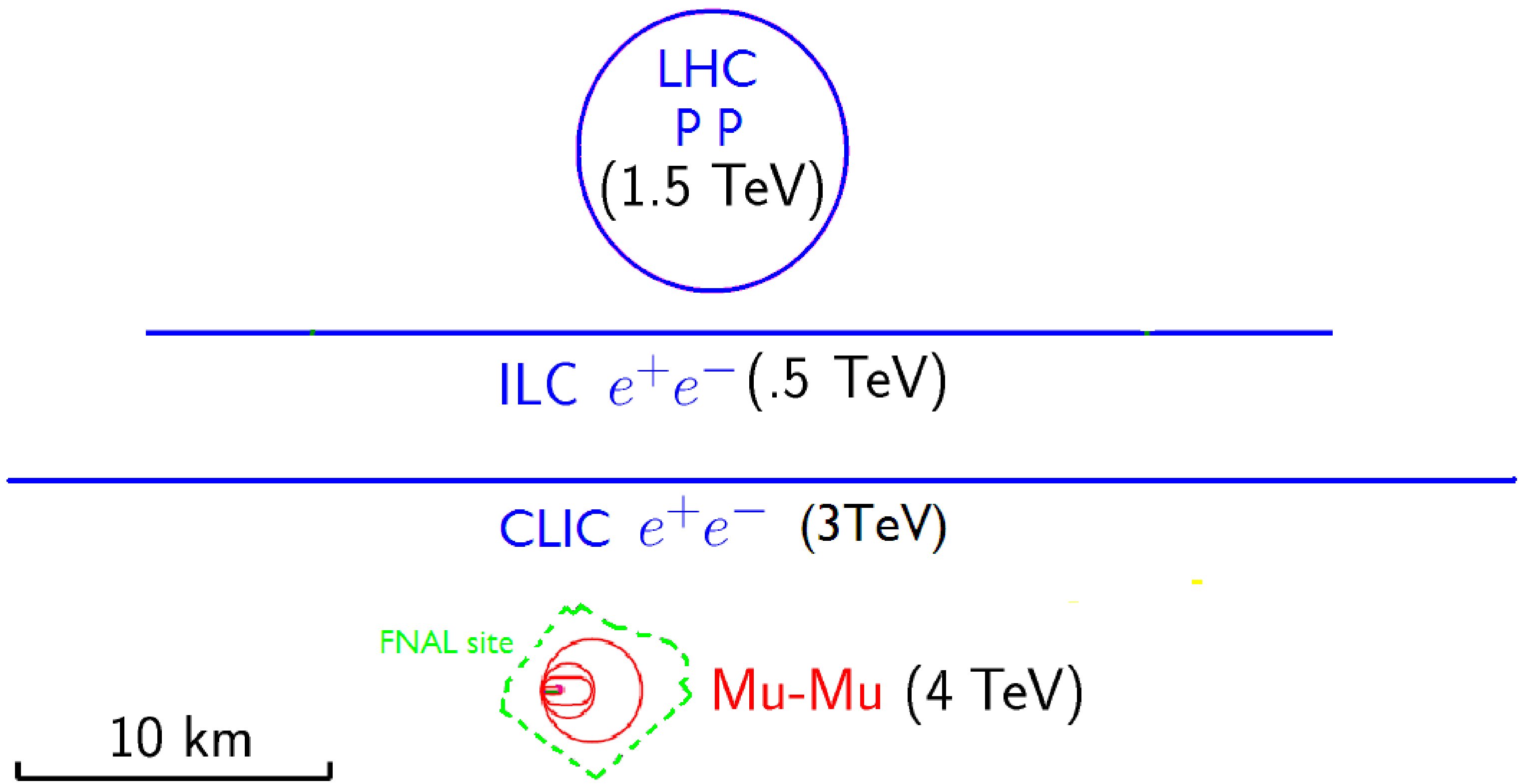
Muon Colliders Design & Simulation

R. B. Palmer (BNL)
LCWS11 Granada, Spain
9/28/11

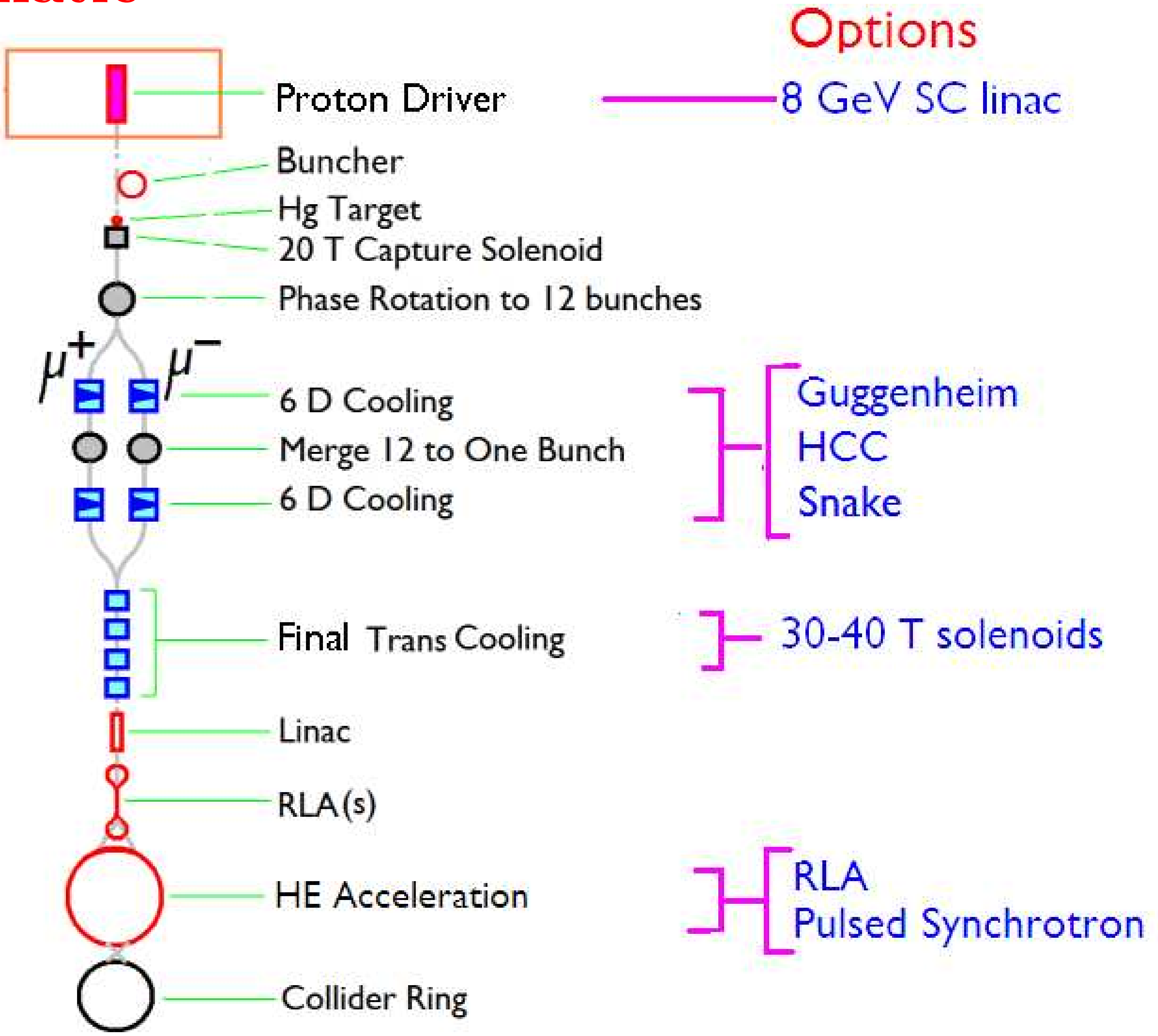
- Introduction to scheme
  - Proton Driver
  - Target and phase rotation
  - Cooling (including space charge)
  - Acceleration
  - Rings (including ν radiation)
- Power consumption & CLIC comparison
- Conclusion

INTRODUCTION



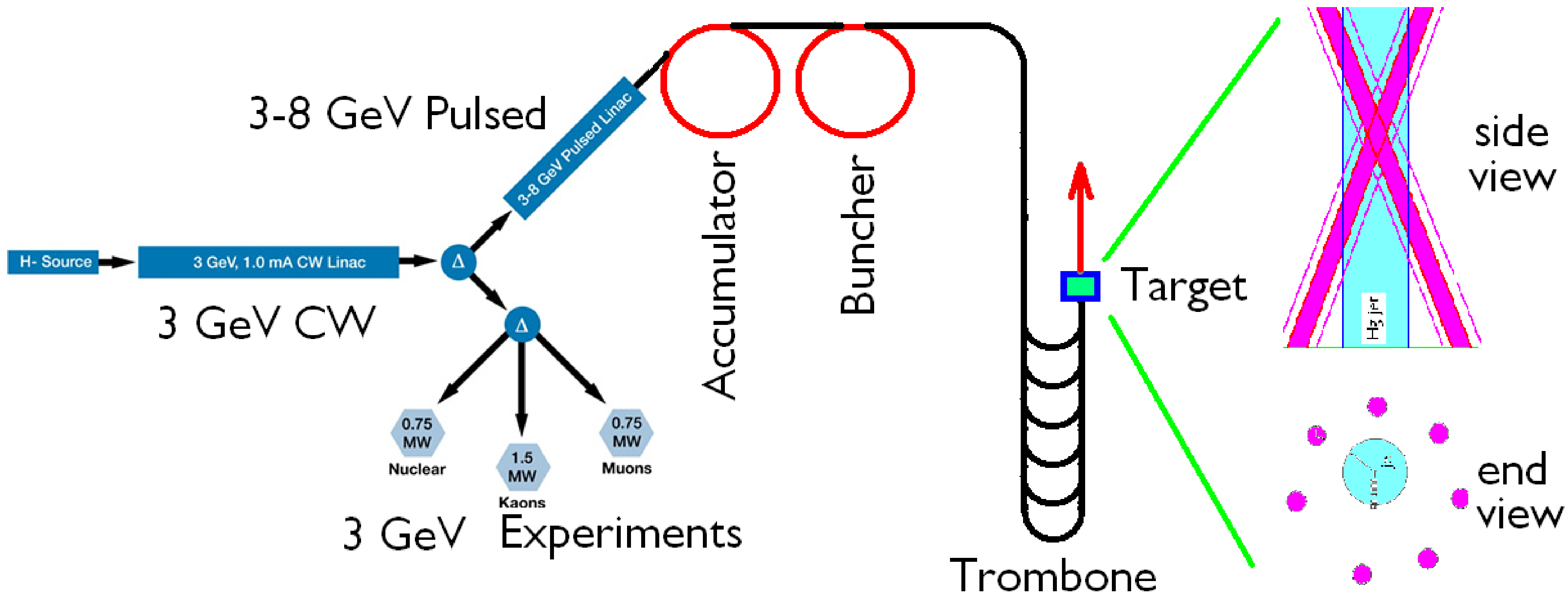
- Muon Colliders certainly smaller,
- Use less power ?
- Cheaper ??
- But certainly less developed

Schematic



Options
Proton Driver
8 GeV SC linac
Buncher
Hg Target
20 T Capture Solenoid
Phase Rotation to 12 bunches
μ+
μ−
6 D Cooling
Merge 12 to One Bunch
6 D Cooling
Guggenheim
HCC
Snake
Final Trans Cooling
30-40 T solenoids
Linac
RLA(s)
HE Acceleration
RLA
Pulsed Synchrotron
Collider Ring

Proton Driver e.g. Project X

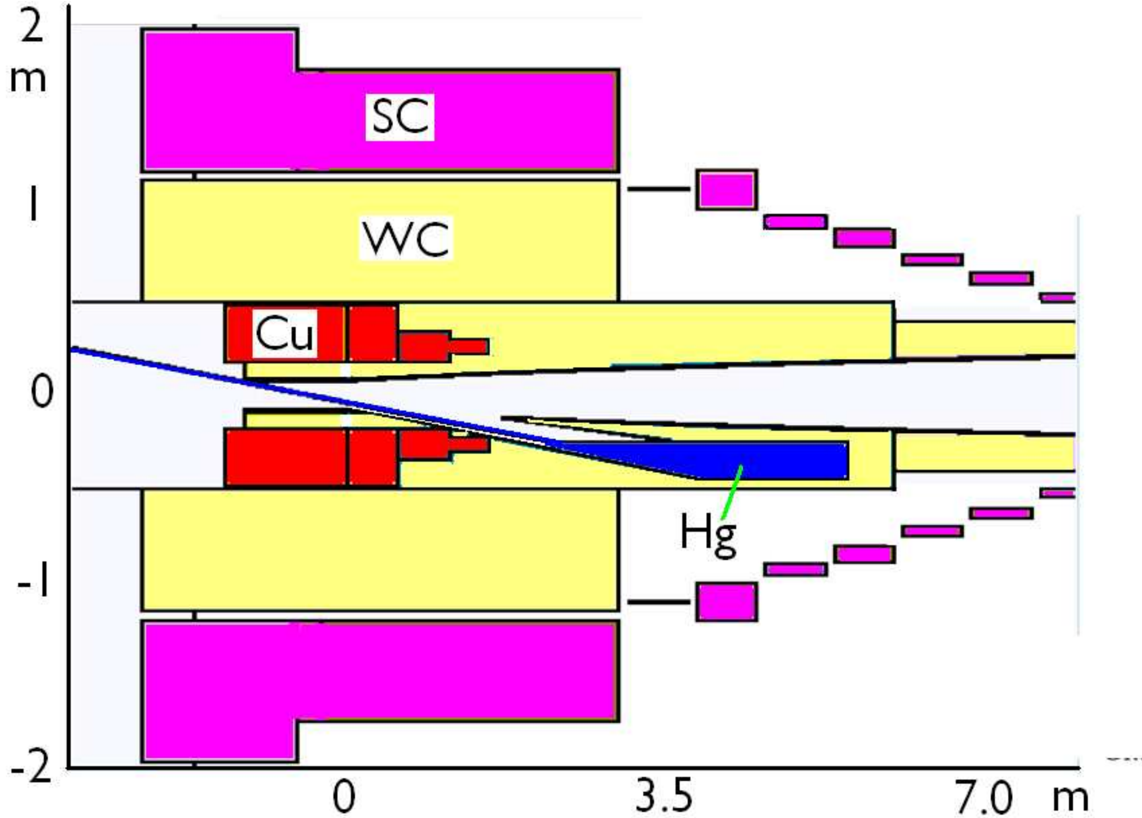


New Task Force on Project X upgrades Gollwitzer

- Upgrade CW linac to 5 mA
- 3-8 GeV Pulsed Linac
- Accumulator, Buncher, and Trombone (Ankenbrandt)

Target & Capture

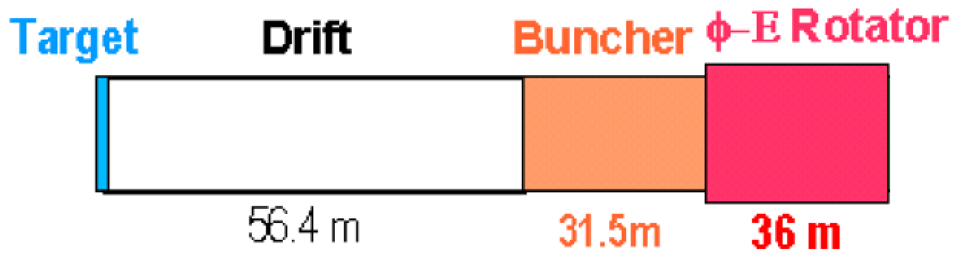
New 20 T Hybrid with increased Shielding

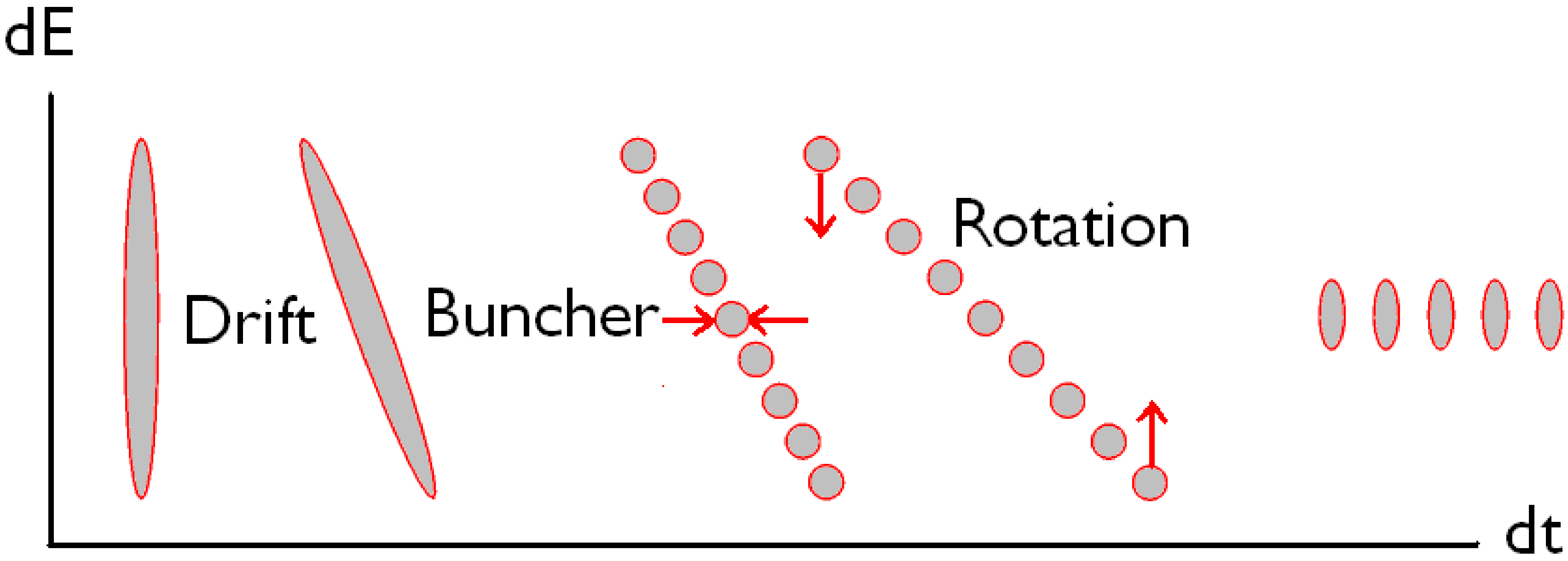


- Copper coil gives 6 T
- Super-conducting solenoid give 14 T, tapering to 3 T
- Tungsten Carbide in water shielding for 4 MW 8 GeV beam
  Cu coil uses 15 MW   SC coil OD is 4 m

New Phase Rotation→12 bunches

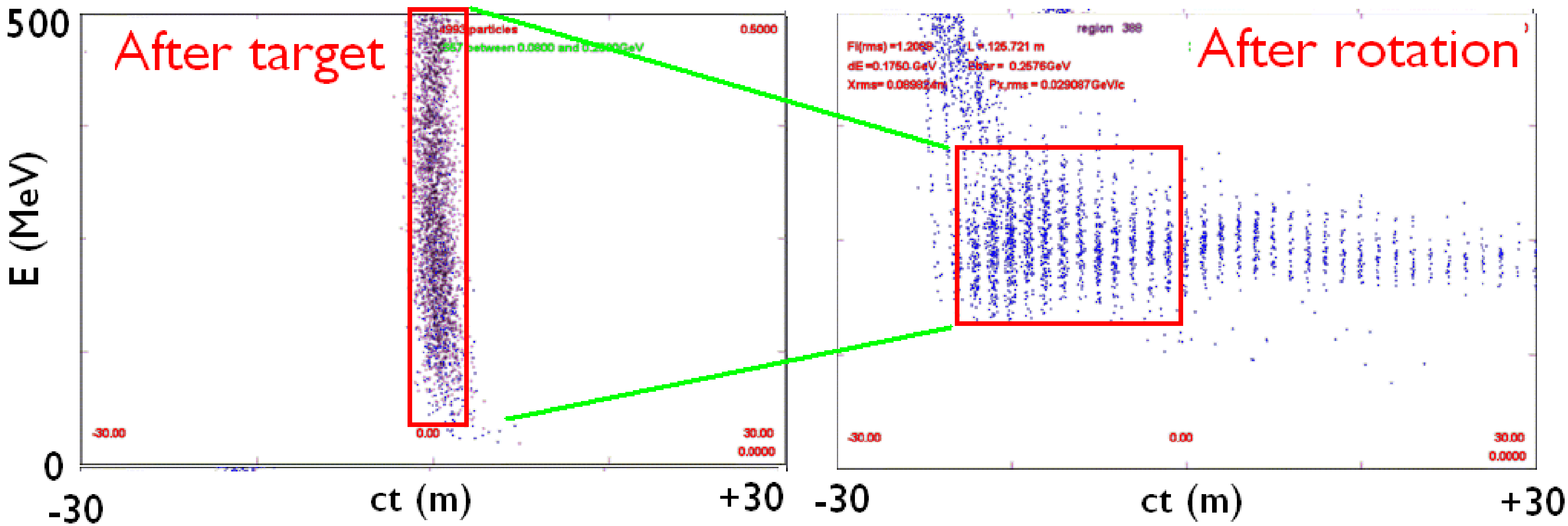
(David Neuffer)





- Large ΔE small $\Delta t \rightarrow$ small ΔE larger Δt

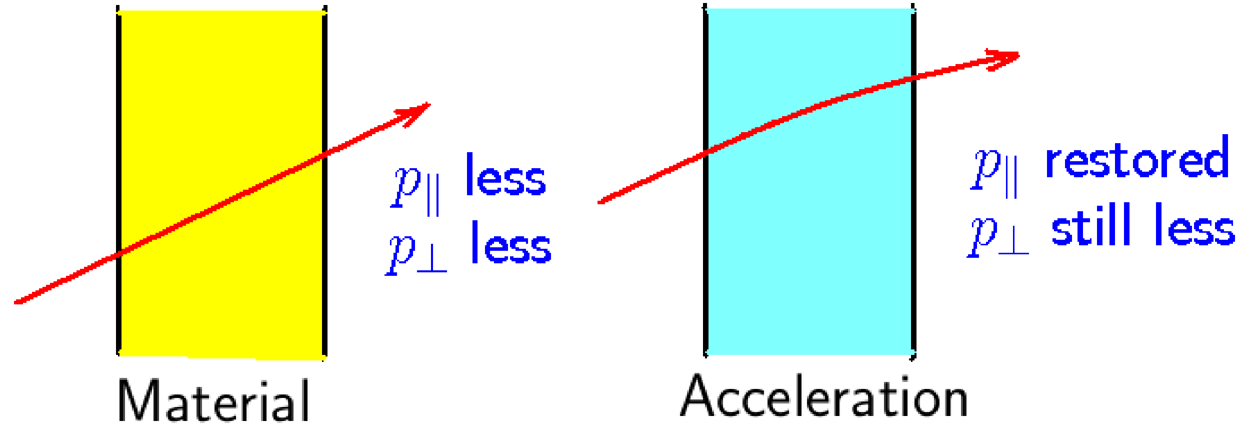
Simulation



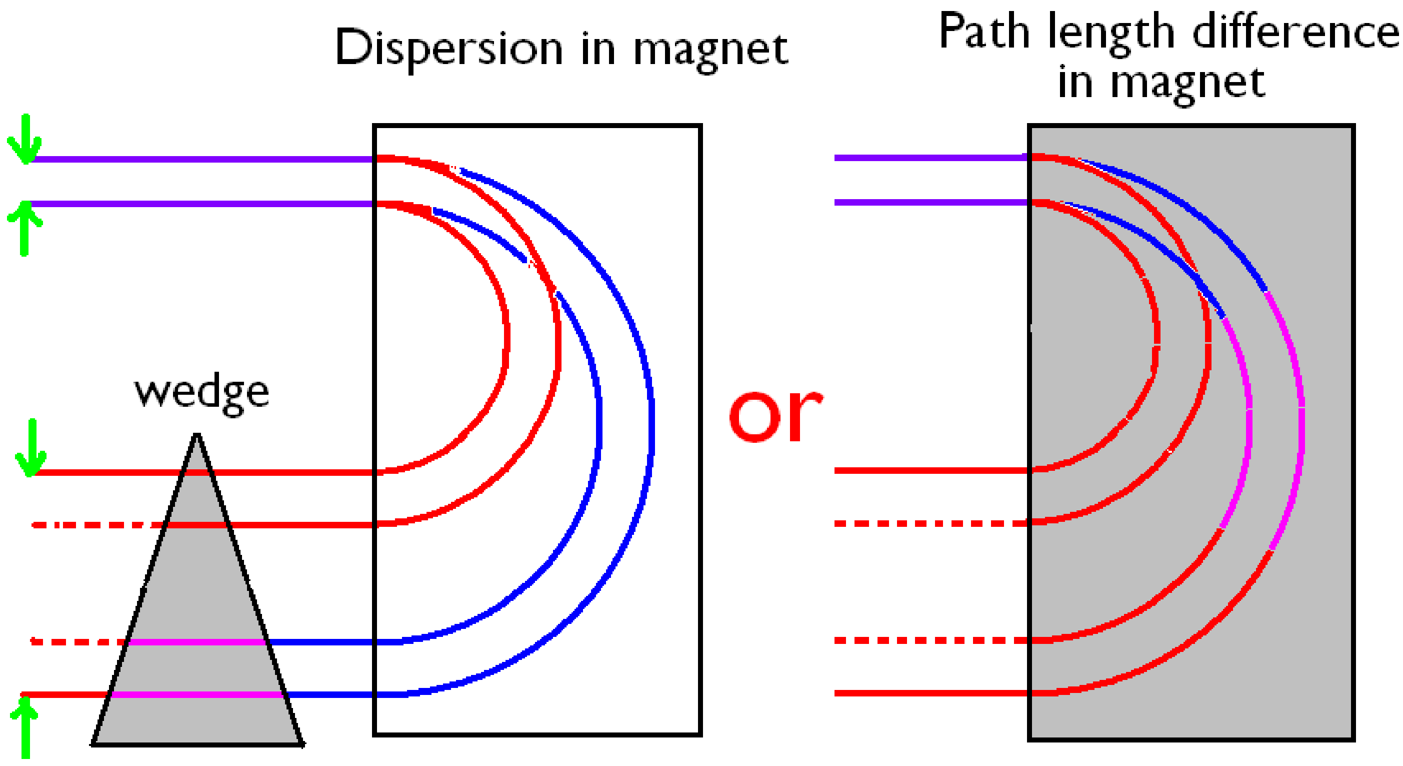
Captures ≈ 48%
of longitudinal phase space

Ionization Cooling

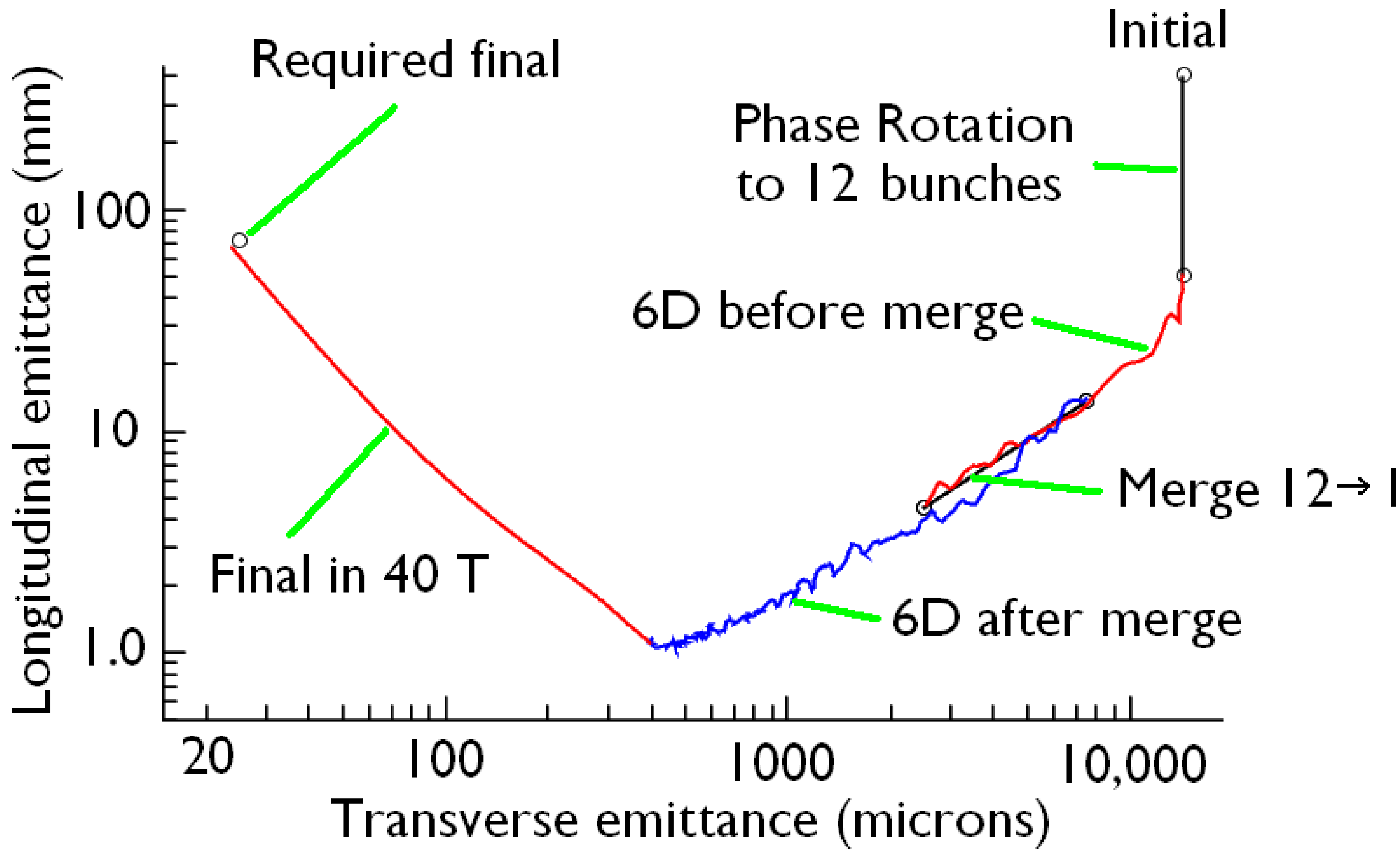
Transverse
(4D)



Longitudinal
(6D)

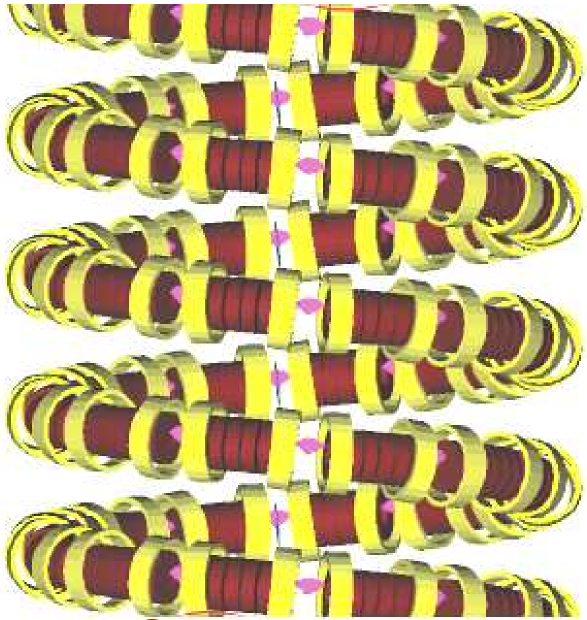


Cooling Sequence (Before Space Charge Calculations)

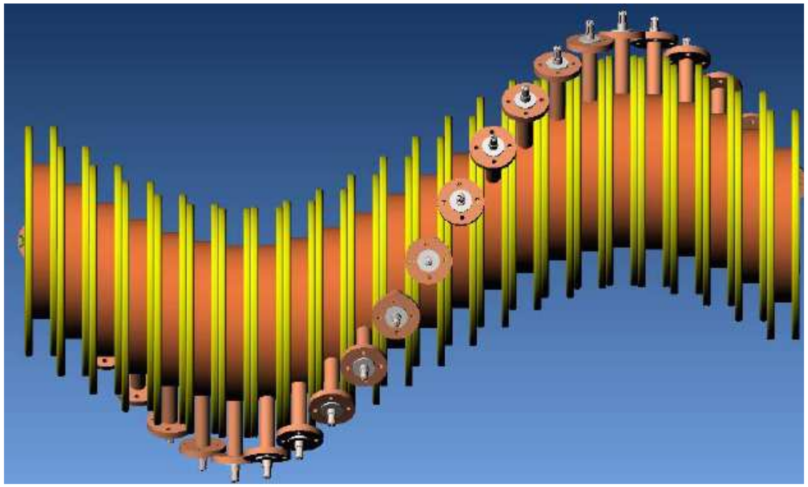


- 6D cooling is best done at ≈ 200 MeV/c
  method runs out at $\epsilon_\perp \approx 400\ \mu m$ & $\epsilon_\parallel \approx 1\ mm$
- To get to lower $\epsilon_\perp$ use highest field (40T) and Low energy
  At low energy long emittance grows, but this now acceptable

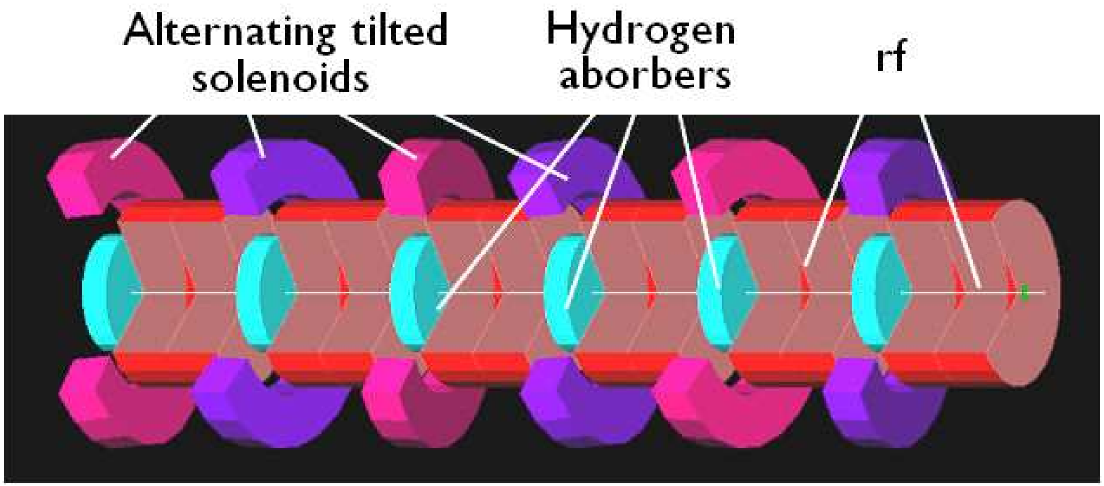
3 candidate 6D cooling lattices



Guggenheim



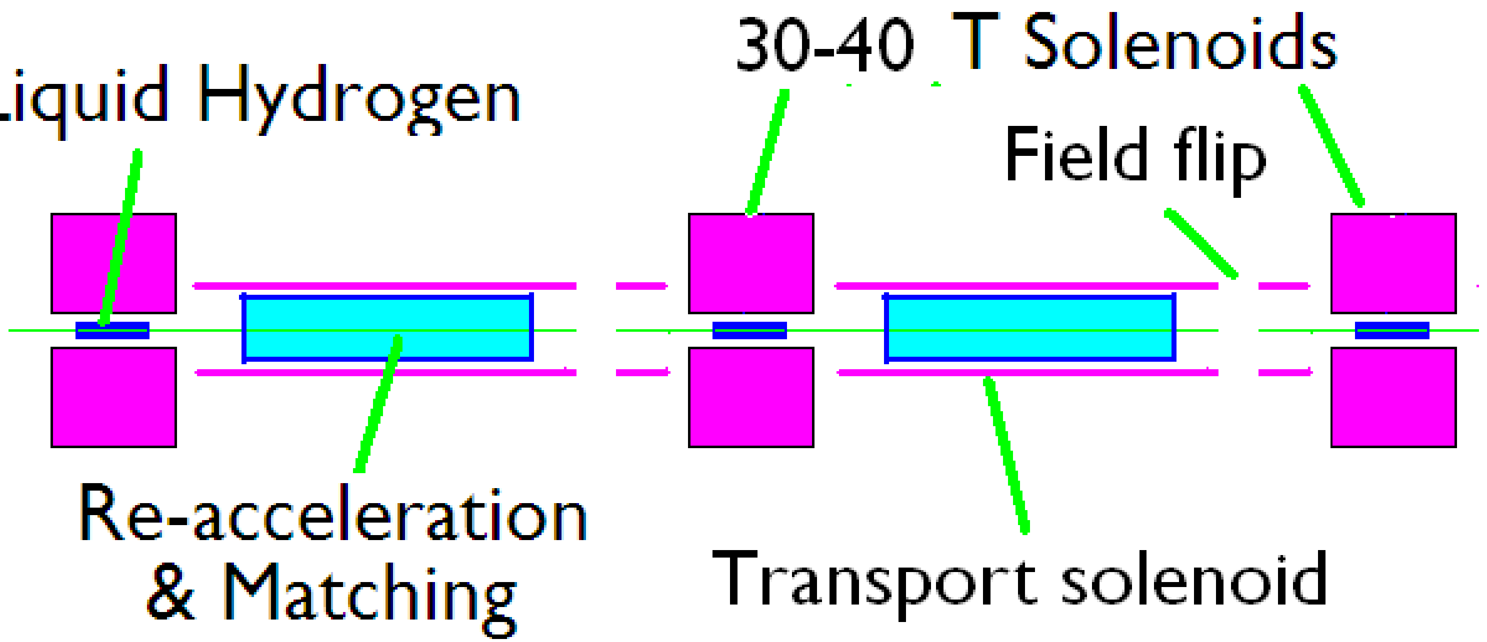
Helical Cooling Channel



Snake

- All simulated   All have problems/limitations
- I will use Guggenheim as example

Final cooling to $\epsilon_\perp = 25\ \mu$ m



- 13 stages
- Cooling in hydrogen simmulated for all
- Matching and re-acceleration simulated only for last 2 stages
  Without space charge simulations look ok
- Circa 40 T HTS in resistive outsert under construction (PBL/BNL SBIR funded)

Space charge

Transverse

$$\frac{\Delta\nu_{\rm space}}{\nu} = \left(\frac{N_\mu}{\sqrt{2\pi}\ \sigma_z}\right) \frac{r_\mu\ \ < \beta_\perp >}{2\ \epsilon_\perp\ \beta_v \gamma^2}$$

For fixed $dp/p, \gamma,\ N_\mu$, then

$$\frac{\Delta\nu_{\rm space}}{\nu} \propto\ \epsilon_z\ \epsilon_{x,y}$$

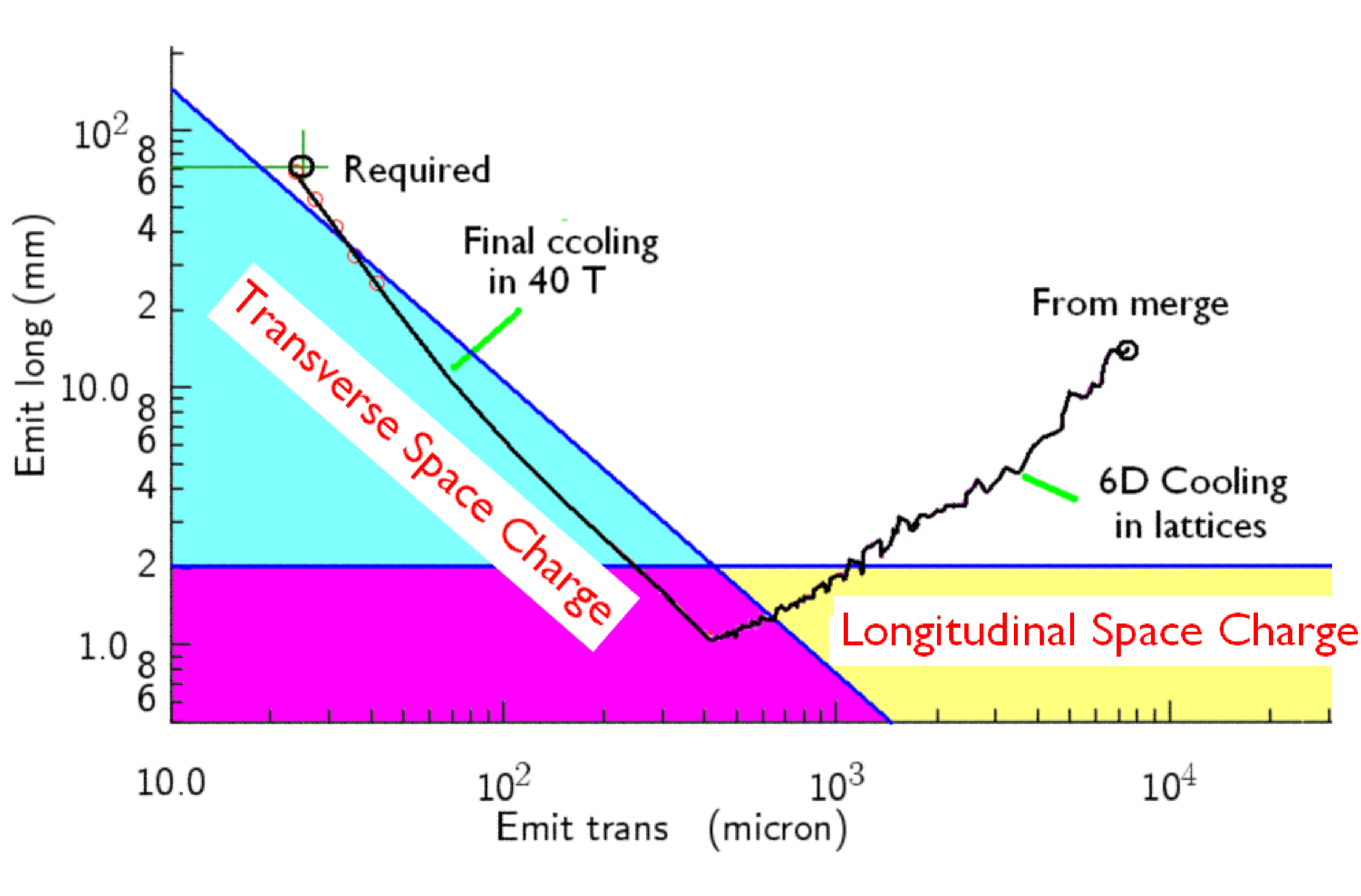
Longitudinal

$$\frac{\mathcal{E}'_{\rm long\ \ sc}}{\mathcal{E}'_{\rm rf\ \ simulated}} = \xi\ \approx\ \frac{0.032\ \ Q\ g\ c}{\epsilon_o\ \gamma^2\ \sigma_z^3\ (\omega\ \mathcal{E}\ \eta\ \ \cos(\phi))_{sim}}$$

For fixed $dp/p, \gamma,\ N_\mu, \mathcal{E}, \omega, \eta$, then

$$\frac{\mathcal{E}'_{\rm long\ \ sc}}{\mathcal{E}'_{\rm simulated}} \propto\ \epsilon_z^3$$

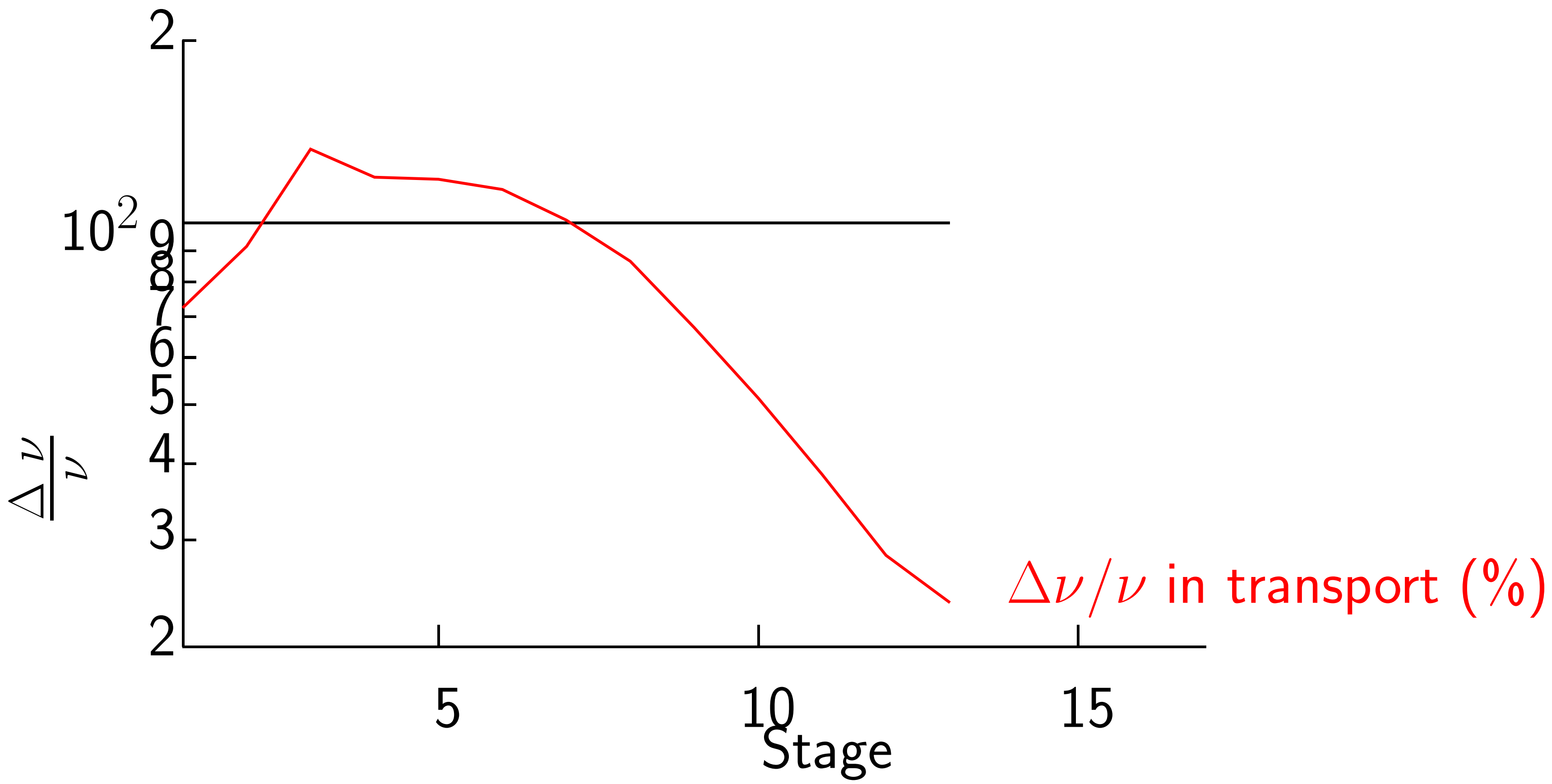
Emittance plot



- Worst: longitudinal at end of 6 D and transverse early in Final

Transverse shifts in final cooling

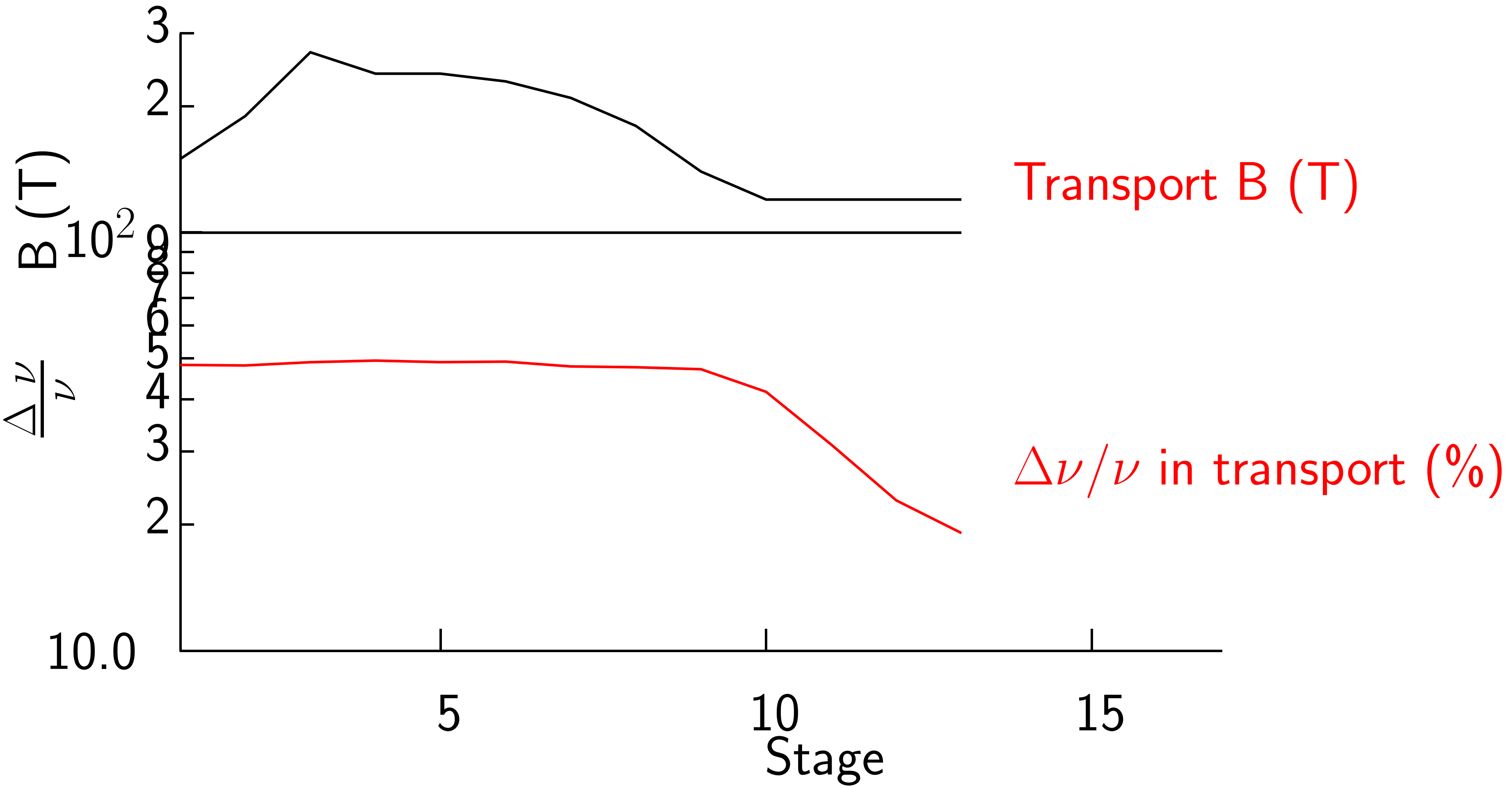
For 1.2 T transport solenoids between 40 T magnets



- This is maximum tune shift at bunch center in transport
- $\Delta\nu/\nu\ > 1$ will certainly not work

Mod Trans shifts in final cooling

With increased transport fields



- $\Delta\nu/\nu \ \leq\ $ 50% probably now ok
- 2.7 T transport not excessive

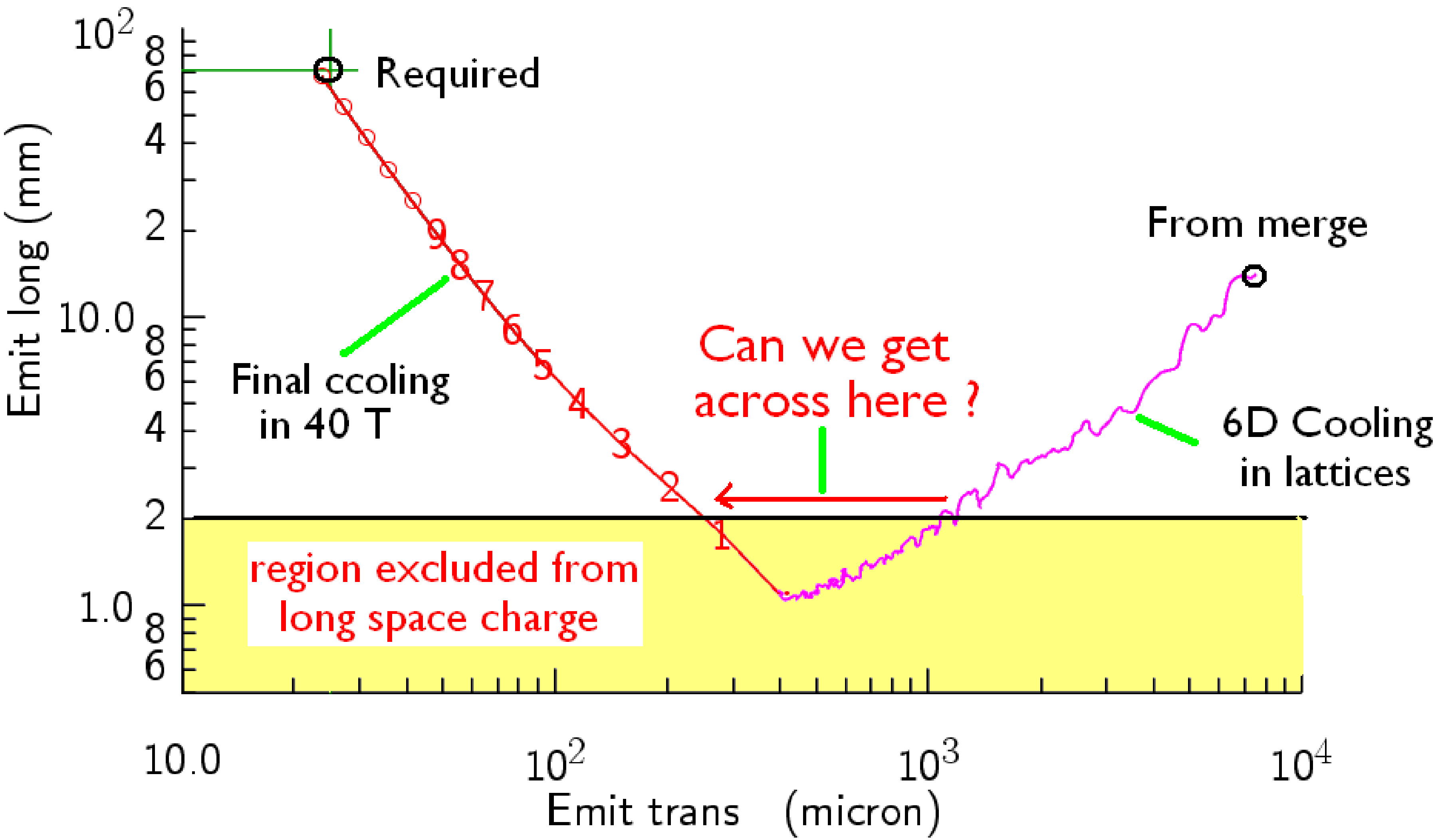
Long space charge at end of 6D

$$\xi = \frac{\mathcal{E}'_{\text{long sc}}}{\mathcal{E}'_{\text{rf simulated}}} \approx \frac{0.032 \;\; Q \; c \;\; g(b/a, \sigma_z/a)}{\epsilon_o \, \gamma^2 \, \sigma_z^3 \, (\omega \, \mathcal{E} \, \eta \; \cos(\phi))_{sim}}$$

N_μ 10^{12}	mom MeV/c	$\epsilon_\parallel$ mm	σ_z mm	freq MHz	$\mathcal{E}_{\text{rf}}$ MV/m	η	b/a	g	$\mathcal{E}'$ MV/m^2	$\mathcal{E}'_{rf}$ MV/m^2	ξ
4.81	207	1.1	16.6	805	20.05	0.5	3	1.75	261	155	1.68

- This will not work
- Probably only fix is to avoid $\epsilon_\parallel \;\leq\; 2 \; (mm)$
- Can we reach the same final emittances without first lowering $\epsilon_\parallel$ so much?

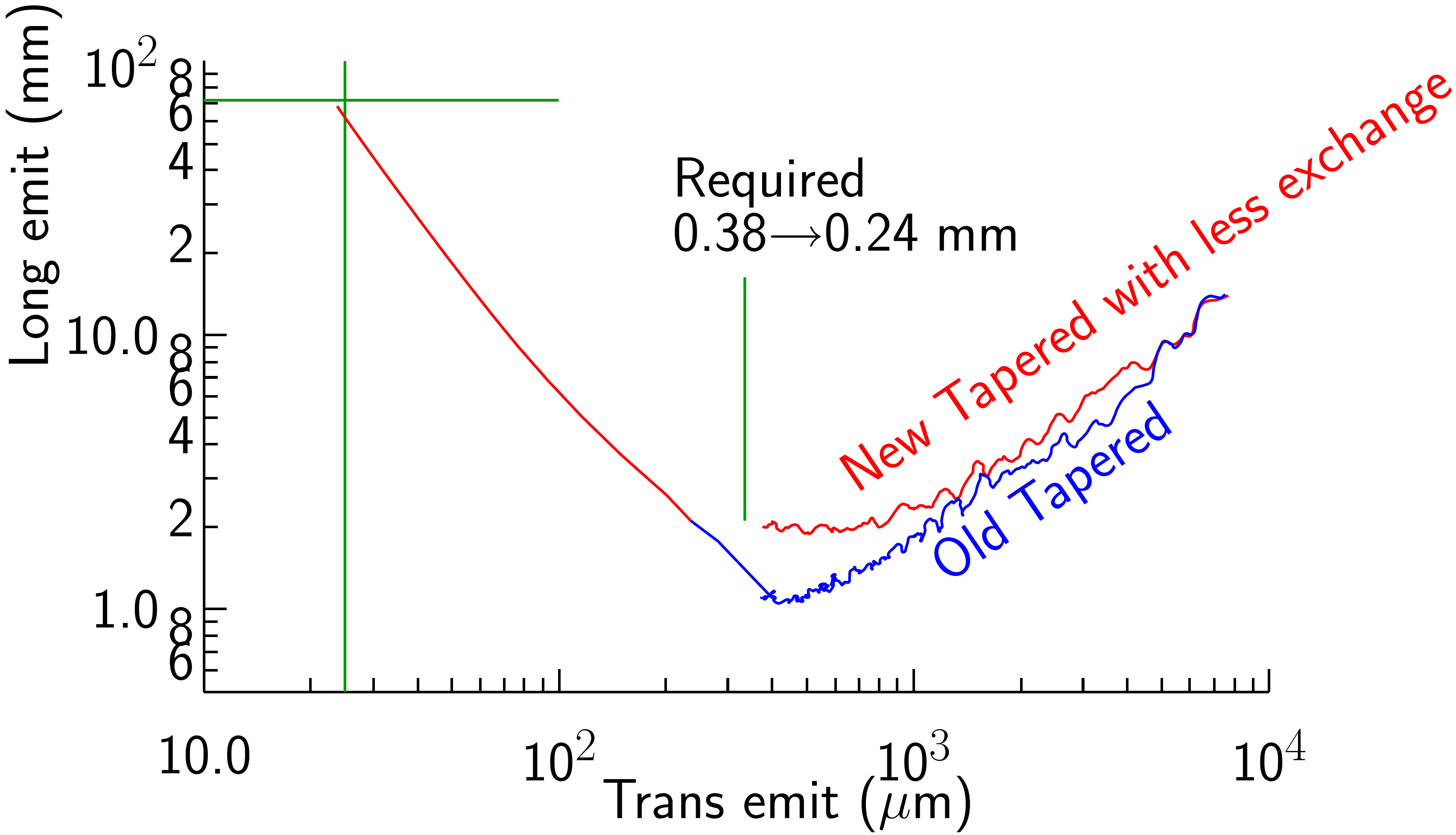
The new cooling challenge



Transverse cooling required to $\epsilon_\perp$=0.24 mm (vs 0.4 mm)

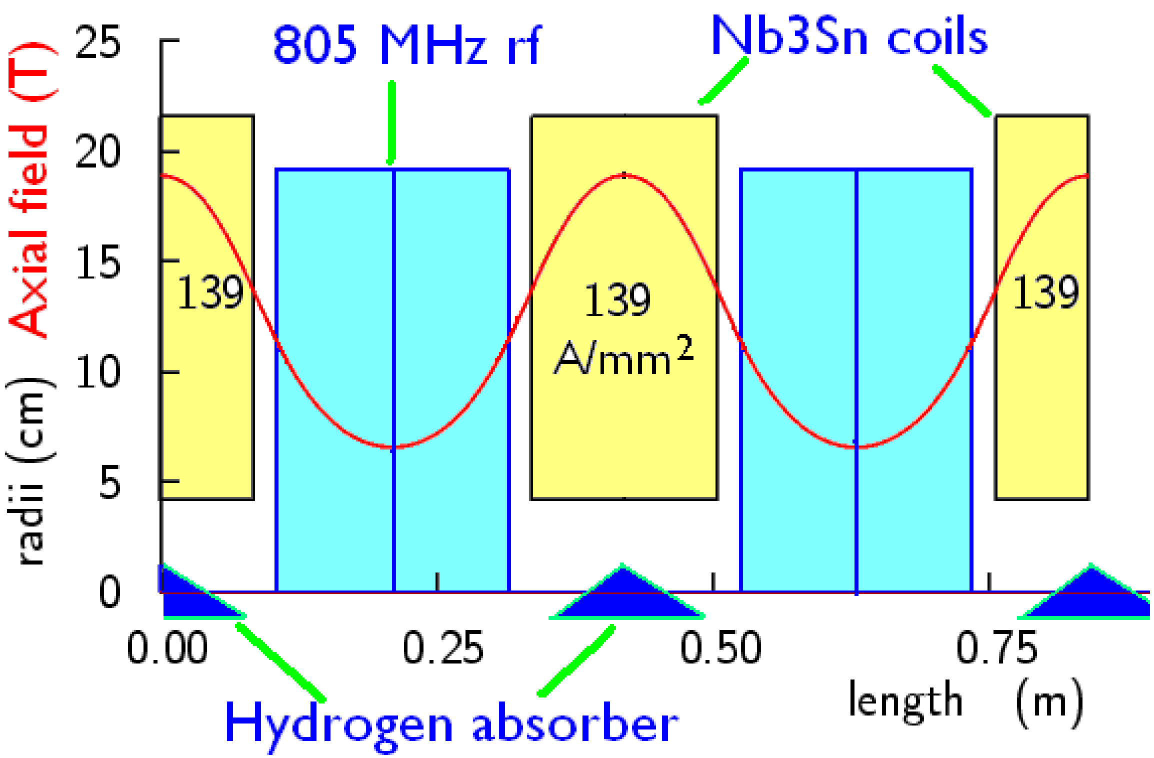
Step I

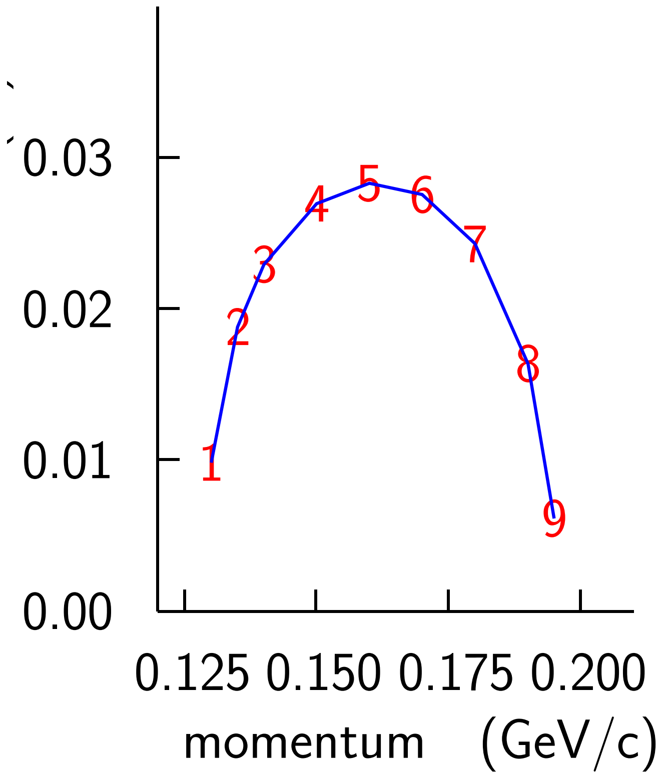
- Weaken emittance exchange to keep $\epsilon_{\|}$ above 2 mm
- This now gives better transverse cooling



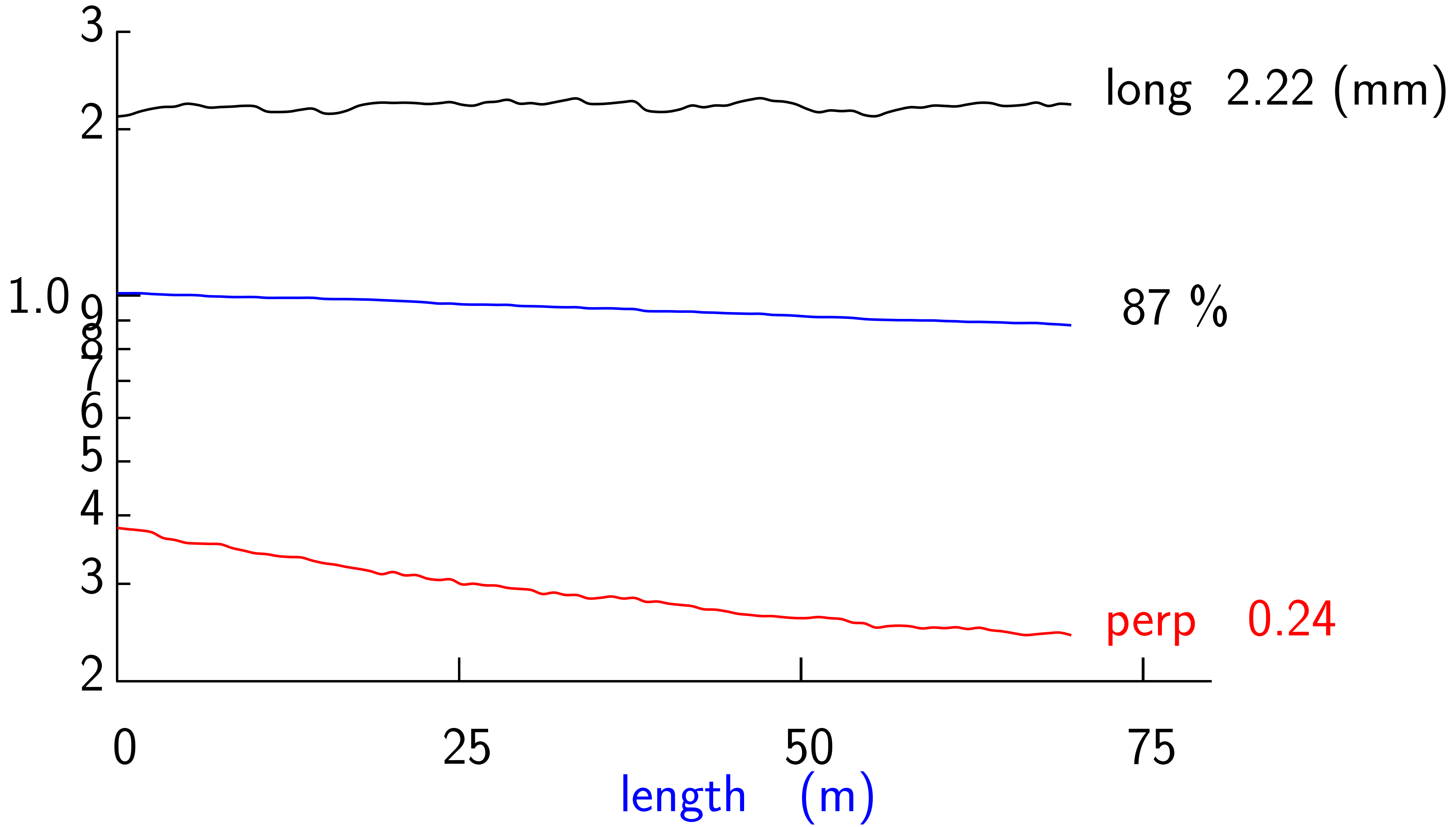
Step II: New non-flip cooling lattice

- 42 cm cell (vs. 68.75), momentum 160 MeV/c (vs. 200)
- Without flips, some angular momentum will be created
- A field flip before first 40 T stage should remove it



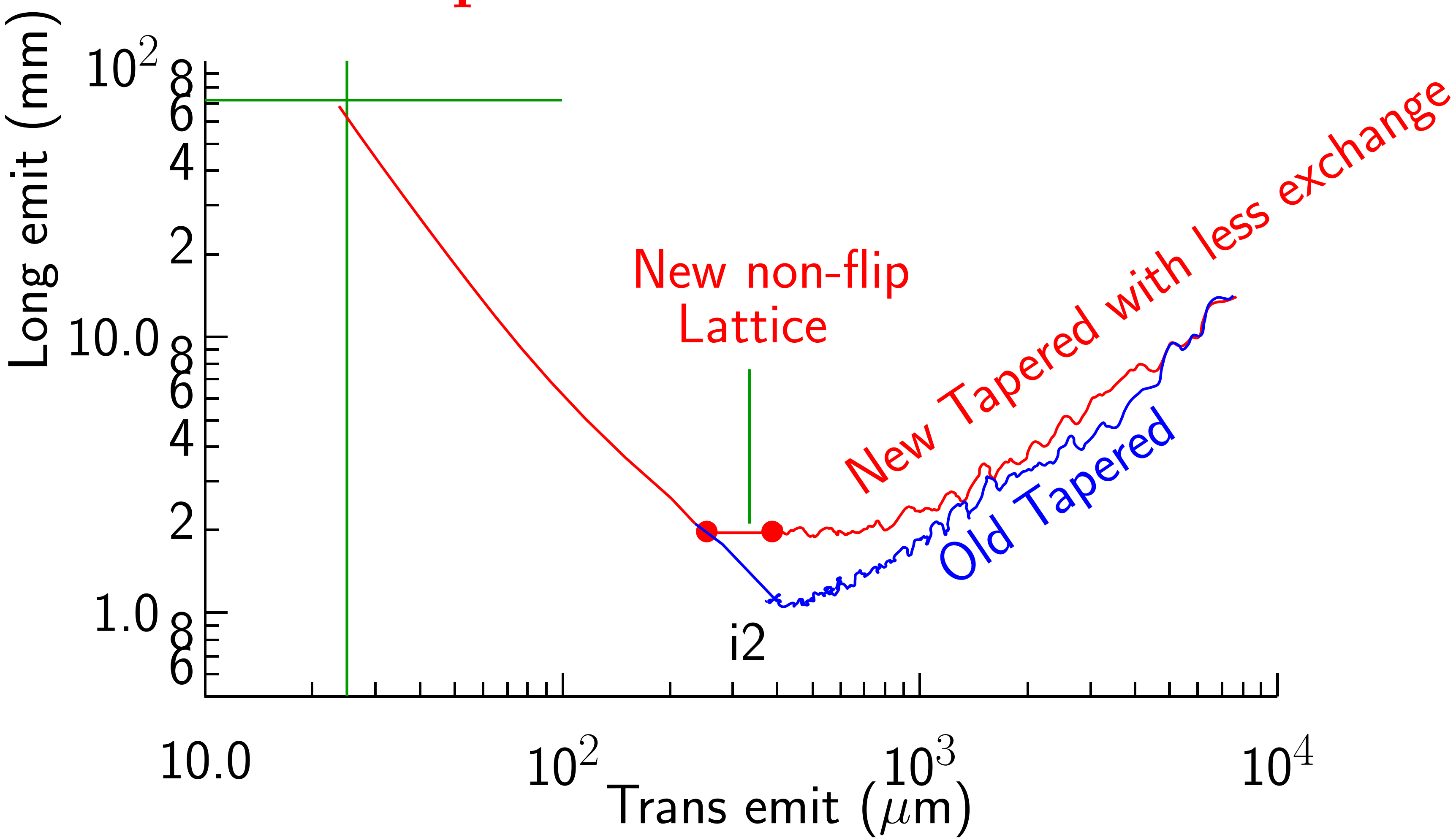


ICOOL Simulation



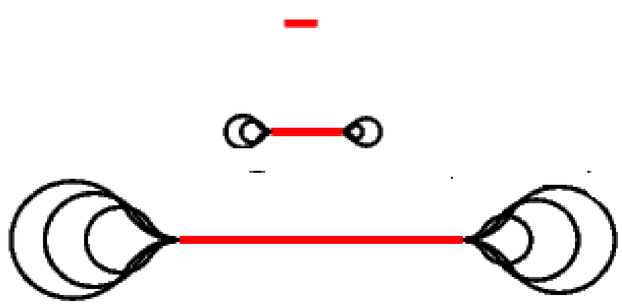
- Required emittance achieved

Emittance plot

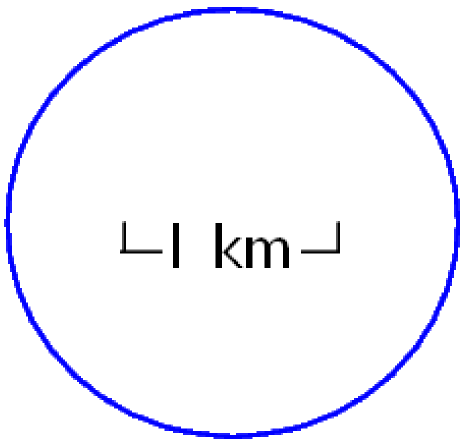


- Problem appears solved
- Fuller simulation - with space charge - required

Acceleration



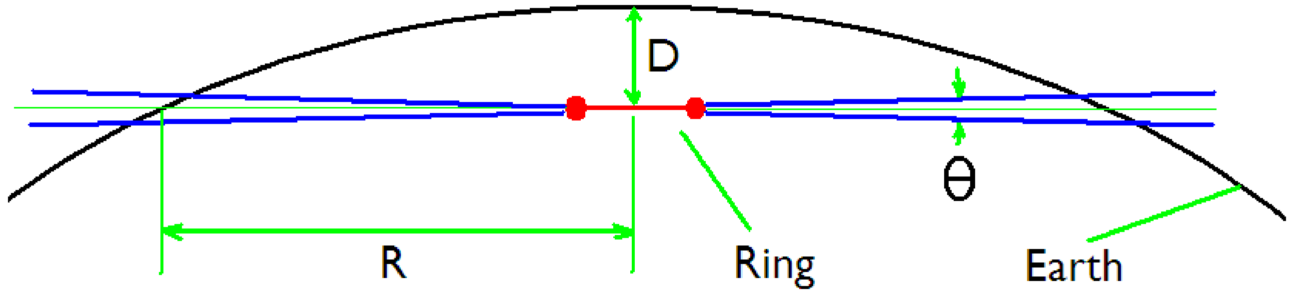
	E GEV		passes	Lengths
1)	.4-1.5	Linac		L(linac)= 68 m
2)	1.5-12.5	RLA	n=4.5	L(linac)= 306 m
3)	12.5-100	RLA	n=6.5	L(linac)= 1250 m
4)	100-400	RCS	n=23	Circ = 6283 m
5)	400-750	RCS	n=27	Circ = 6283 m



both RCS pulsed at 15 Hz

- Transmission 65.2 %

Neutrino Radiation



$$R_B = 4.4\,10^{-24} \frac{N_\mu\ f\ E^3\ t\ \ < B >}{D\ B}\ \ \text{Sv} \quad \text{from regions of uniform B}$$

$$R_L = 6.7\,10^{-24} \frac{N_\mu\ f\ E^3\ t\ \ < B >\ \ L}{D}\ \ \text{Sv} \quad \text{from straight sections}$$

For $R_B = R_L$ = 10% Fed limit = 0.1 mSv (10 mRad)

E TeV	B(min) T	L(max) m
1.5	0.25	2.4
3.0	1.5	0.28

But final focus is a special case because divergence is so large

MC Rings

3 TeV design is new; 6 TeV design is extrap. for same ν radiation

C of m Energy	1.5	3	6	TeV
Luminosity	1	4	12	10^{34} cm^{2}sec^{-1}
Muons/bunch	2	2	2	10^{12}
Total muon Power	7.2	11.5	11.5	MW
Ring $<$bending field$>$	6.04	8.4	11.6	T
Ring circumference	2.6	4.5	6	km
β^* at IP $= \sigma_z$	10	5	2.5	mm
rms momentum spread	0.1	0.1	0.1	%
Depth	135	135	540	m
Repetition Rate	15	12	6	Hz
Proton Driver power	4	3.2	1.6	MW
Muon Trans Emittance	25	25	25	pi μm
Muon Long Emittance	72,000	72,000	72,000	μm

Note: Muon parameters the same for all energies

ESTIMATED WALL POWER

	Len m	Static 4^o MW	Dynamic rf MW	— PS MW	— 4^o MW	— 20^o MW	Tot MW
p Driver (SC linac)							(20)
Target and taper	16			15.0	0.4		15.4
Decay and phase rot	95	0.1	0.8		4.5		5.4
Charge separation	14						
6D cooling before merge	222	0.6	7.2		6.8	6.1	20.7
Merge	115	0.2	1.4				1.6
6D cooling after merge	428	0.7	2.8			2.6	6.1
Final 4D cooling	78	0.1	1.5			0.1	1.7
NC RF acceleration	104	0.1	4.1				4.2
SC RF linac	140	0.1	3.4				3.5
SC RF RLAs	10400	9.1	19.5				28.6
SC RF RCSs	12566	11.3	11.8				23.1
Collider ring	2600	2.3		3.0	10		15.3
Totals	26777	24.6	52.5	18.0	21.7	8.8	145.6

Similar calculations for 3 TeV give Wall power = 159 MW

Similar calculations for 6 TeV give less Wall power

Compare 3 TeV $\mu^+\mu^-$ with e^+e^- CLIC

		$\mu^+\mu^-$	e^+e^-
Luminosity	10^{34} cm^{2}sec^{-1}	4	2
Detectors		2	1
β^* at IP $= \sigma_z$	mm	5	0.09
Lepton Trans Emittance	μm	25	0.02
rms bunch height	μm	4	0.001
Total lepton Power	MW	11.5	28
Proton/electron Driver power	MW	3.2	188
Wall power	MW	159	465

- $\mu^+\mu^-$ luminosity twice CLIC's (for dE/E $< 1\%$) & 2 detectors
- Spot sizes and tolerances much easier than CLIC's
- Wall power $\approx 1/3$ CLIC's
- But less developed
- Muon Accelerator Program (MAP) $\rightarrow$ Feasibility Study

CONCLUSION

- Much simulation progress this year
  - new capture magnet design, shorter phase rotation, charge separation & merge designs, 6D cooling simulations, sequence of acceleration with better transmission, design of tungsten shield pipe Detector background studies
- Space charge effects are significant
  - but appear soluble
- Remaining major challenge
  - rf breakdown in magnetic fields Solutions being tested
- Favorable comparisons with CLIC:
  - Luminosity greater than CLIC's
  - Estimated wall power $\approx 1/3$ of CLIC
- Extrapolation to higher energies thinkable